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I submit herewith the completed original of the Final Report for the grant entitled: "Improvements to passive acoustic tracking methods for marine mammal monitoring".

Sincerely,

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14. ABSTRACT
This project investigated and implement several methods to improve the accuracy, efficiency, and applicability of model-based passive acoustic methods to track marine mammals. Methods were developed and tested that: 1) Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position. 2) Use improve maximization schemes in model-based tracking. 3) Use received sound pressure levels in addition to arrival times for tracking. This project also developed methods to simultaneously track multiple animals in cases where it is difficult/ impossible to separate and associate calls from individual animals.

15. SUBJECT TERMS
Marine mammal; Passive acoustic monitoring; Localization; Tracking; Multiple source; Sparse array

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FINAL REPORT

Improvements to Passive Acoustic Tracking Methods for Marine Mammal Monitoring

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LONG-TERM GOALS

The long-term goal of this project was to improve model-based passive acoustic methods for tracking marine mammals. When possible, tracking results were used to study marine mammal behavior and bioacoustics.

OBJECTIVES

The first three objectives of this project were to investigate and implement several specific ideas that had potential to improve the accuracy, efficiency, and applicability of model-based passive acoustic tracking methods for marine mammals:

1) Inverting for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position.
2) Improving maximization schemes used in model-based tracking.
3) Using information in addition to arrival times for tracking.

The final objective of this project was to:

4) Improve and test approaches to simultaneously track multiple animals in cases where it is difficult/impossible to separate and associate calls from individual animals.

APPROACH

Eva-Marie Nosal was the key individual participating in this work as the principal investigator and main researcher. She supported and advised several graduate students who contributed to the project.

This project used existing datasets. The main effort was directed toward data collected at Navy Ranges. Other datasets that use bottom-mounted sensors were also considered when available and appropriate. The main species of interest in these datasets were sperm whales, beaked whales, minke whales, and humpback whales. Most methods developed are generalizable to other species.

This project used model-based tracking methods [e.g. Tiemann et al. 2004; Thode 2005; Nosal 2007] to localize animals in situations where straight-line propagation assumptions made by conventional marine mammal tracking methods fail or result in unacceptably large errors. In the model-based approach, a source is localized by finding the position that gives predicted arrival times that best match the measured arrival times. This is done by creating an ambiguity surface that gives the probability of an animal at any position in space. The maxima of this surface give the estimated animal position(s). Arrival time predictions are made using a sound propagation model, which in turn uses information about the environment including sound speed profiles and bathymetry. Calculations are based on measured time-of-arrivals (TOAs) or time-differences-of-arrival (TDOAs), modeled TOAs/TODAs, estimated uncertainties, and any available a priori information. All methods are fully automated through MATLAB code.

The approaches taken for each of the objectives are further expanded separately below:

Objective 1: <u>Invert for sound speed profiles, hydrophone position and hydrophone timing offset in addition to animal position</u>

Almost all marine mammal tracking methods treat animal position as the only unknown model parameter. Other parameters (sound speed, hydrophone position, hydrophone timing) are treated as known inputs and estimated error in these "knowns" is propagated to give error in estimated animal position. This is not always the best approach since it can cause location errors to become unnecessarily large. Moreover, small offsets in hydrophone timing lead to entirely incorrect position estimates (and unfortunately timing is a serious practical problem for passive acoustic tracking systems that comes up repeatedly in real-world datasets). There are also situations in which sound speeds, phone position and/or timing offsets are entirely unknown.

Sound speed, phone position and/or timing offsets can be readily be included in the set of unknown model parameters in model-based tracking, with any known information incorporated as *a priori* information. This approach can yield much improved position estimates and/or to give position estimates in cases that would be otherwise impossible. This approach has been used successfully by the underwater acoustics community [e.g. Collins and Kuperman, 1991; Fialkowski et al. 1997; Tollefsen and Dosso, 2009] but modifications for and application to marine mammal tracking were limited [but see Thode 2000].

Objective 2: <u>Improve maximization schemes used in model-based tracking</u>

In past model-based localization work, ambiguity surface maximization was implemented using a grid search (sometimes using multiple-step approach starting with coarse grids that are successively refined). This part of the project implemented more sophisticated maximization schemes to find local maxima in the ambiguity surfaces. Benefits of using these schemes include reduced run times and more precise position estimates. In addition, one serious drawback of the approach from Objective 1 (increased parameter space) is increased computational complexity due to larger search spaces; using more sophisticated maximization schemes was critical to keep the problem computationally viable.

Objective 3: Use information in addition to arrival times for tracking

Almost all marine mammal tracking methods rely solely on arrival times. There is often additional information that changes with animal position and can consequently be used to obtain/improve position estimates. Several researchers have used sound pressure level or propagation characteristics for tracking [e.g. Cato 1998; McDonald and Fox 1999; McDonald and Moore 2002; Wiggins et al. 2004]. Past approaches have generally been limited to assumptions of omni-directional sources and spherical spreading; assumptions that do not always apply. With some modification, the model-based localization methods used in this project can incorporate source levels and transmission loss and account for confounding factors such as source directionality.

Objective 4: Multiple animal tracking

One approach taken to track multiple animals involves developing source separation methods that are applied prior to tracking. Once sources have been separated on each hydrophone, the association problem (identifying the same call on all hydrophones) is greatly simplified. If multiple animals can thus be separated and calls associated, the problem is reduced to multiple applications of single-animal tracking methods. In this project, different approaches for multiple animal tracking were explored for cases in which source separation/association is not possible.

WORK COMPLETED

Objective 1:

The usefulness of inverting for sound speed profile (SSP) in addition to animal position was demonstrated using minke whale boings at PMRF (7 hydrophone localization dataset from the 2011 Workshop on Detection, Classification and Localization (DCL) of Marine Mammals). The animals were expected to be relatively close to the surface (since baleen whales are generally not deep divers). Since sound speed varies most near the surface (due to heating/cooling and mixing effects), the effect of sound speed profile (SSP) uncertainty was expected to be of some significance in this case. Sound speed was assumed to vary with depth but not with range or time. Principal component analysis of monthly historical SSPs was used to reduce the dimensionality of the SSP space. In the inversion, SSP was modeled as the mean SSP over all months plus a linear combination of the first 3 principal components (retaining those characteristics that contribute most to

SSP variance and ignoring the higher-order components). Inversion for SSP was applied globally over all localized calls.

Objective 2:

A simple downhill simplex optimization scheme (Neadler-Meade) was implemented for the PMRF minke whale dataset. The optimization scheme consistently converged to value near the correct maxima and overall run times were reduced by ~10 times when compared with a grid-search method (which successively refines grid spacing as the algorithm "zooms in" on the final solution). The same approach was applied to the AUTEC sperm whale localization datasets from the 2005 DCL Workshop and worked well in cases with relatively simple ambiguity surfaces (i.e. small parameter spaces and few peaks from few animals and well-associated calls).

In past work, modeled SSP-dependent arrival times were obtained by interpolating from pre-computed values over a grid of ranges and depths. Although feasible and accurate, this approach creates a computational bottleneck; the interpolation step requires several operations which, although minimal for a single iteration, become burdensome when repeated over thousands/millions of iterations. To relieve this burden, an approach that parametrizes the modeled arrival time surface to give a closed-form analytical expression that gives arrival time as a function of range and depth was developed. This is accomplished by fitting a best-fit polynomial surface to the arrival time offset between a travel times obtained using a constant sound speed model and a depth dependent sound speed model.

Objective 3:

Theory was developed to localize marine mammals using received sound pressure level. The approach (dubbed the "received level difference method", RLD) uses differences in received sound pressure levels in the same way that that time-differences of arrival are used in model-based time of arrival localization methods. A source is localized by finding the position that gives predicted sound pressure levels that best match measured sound pressure levels. Sound pressure level predictions are made using a sound propagation model, which in turn uses information about the environment including sound speed profiles and bathymetry. The method relies on assumptions of omidirectional sources and calibrated hydrophones. The method is illustrated in Figures 1. Simulations to explore and quantify the performance of the RLD method were performed and application to several datasets were made.

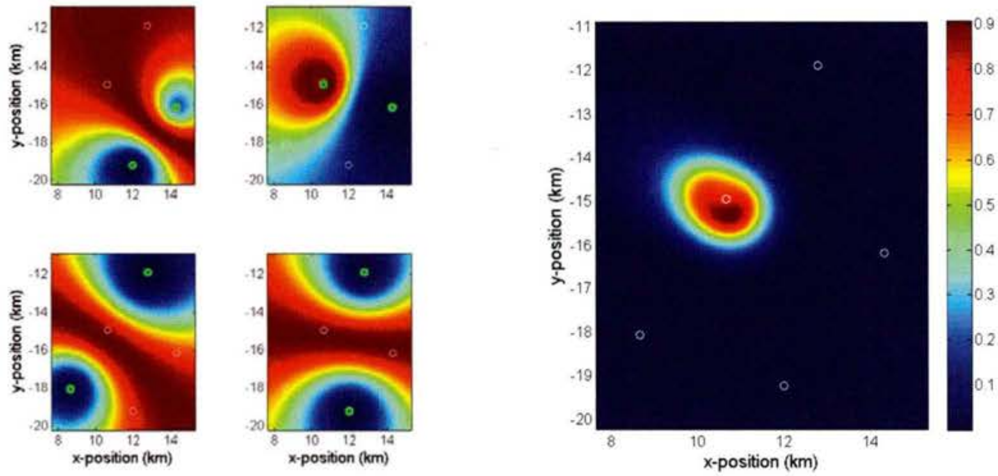

Figure 1. Left: For each hydrophone pair (green circles), ambiguity surfaces (red/blue indicate high/low probability of source presence) are formed from the difference in sound pressure levels received at the two phones. Right: Multiplying ambiguity surfaces from all receiver pairs reveals the source location.

The RLD method was subsequently extended to a method that uses both arrival times and received levels. This is accomplished by forming an ambiguity surface that combines travel time surfaces with received-level surfaces via a weighted multiplication of the two surfaces.

A source level localization method (henceforth referred to as the "received level method", RL) was developed that includes source sound pressure level as an unknown parameter. This differs from the RLD method in that it solves for source level directly rather than using differences in received source levels between hydrophone pairs. Doing this is analogous to using time of arrivals (TOAs) and solving for sound emission time instead of using time-differences of arrival (TDOA) [see Nosal 2013 for a detailed discussion of this difference].

Objective 4:

Theory was developed for the "multiple animal time-difference-of-arrival localization" (MTDOA) and "multiple animal time-of-arrival localization" (MTOA) methods. These methods extend model-based tracking to cases with multiple animals and/or cases where call association and/or classification are difficult/impossible. The methods result in multi-modal ambiguity surface in which persistent peaks are tracked over time to estimate produce animal locations/tracks.

The MTOA method was extended to make use of higher order (e.g. multipath) arrivals. To accomplish this, the set of hydrophone used for localization is augmented with virtual hydrophones that correspond to the expected higher-order arrivals.

The MTOA and RL methods were combined to produce a method (MTOA+RL) that uses both arrival times and received levels to estimate source locations. The unknown parameters that are inverted for include source emission times, source levels, and animal positions. Because of the large parameter space involved, implementation relies heavily on the improved maximization schemes implemented as part of Objective 2.

RESULTS

Objective 1:

Including SSP in inversions results in tighter peaks in the localization ambiguity surfaces since data and model are better matched by including inversion for SSP in the process. In the datasets considered, this reduced 95% confidence intervals in position estimates by 2-5 times. It also returned a sound speed profile estimate.

Objective 2:

In relatively simple cases (e.g. single animal, well-associated calls) the model-based ambiguity surfaces have single peaks. In these cases, the optimization schemes introduced in this project worked efficiently and well and significantly improved run-times. The methods were successfully applied to more complicated cases (e.g. multi-modal ambiguity surfaces resulting from multiple animals and/or mis/un-associated calls).

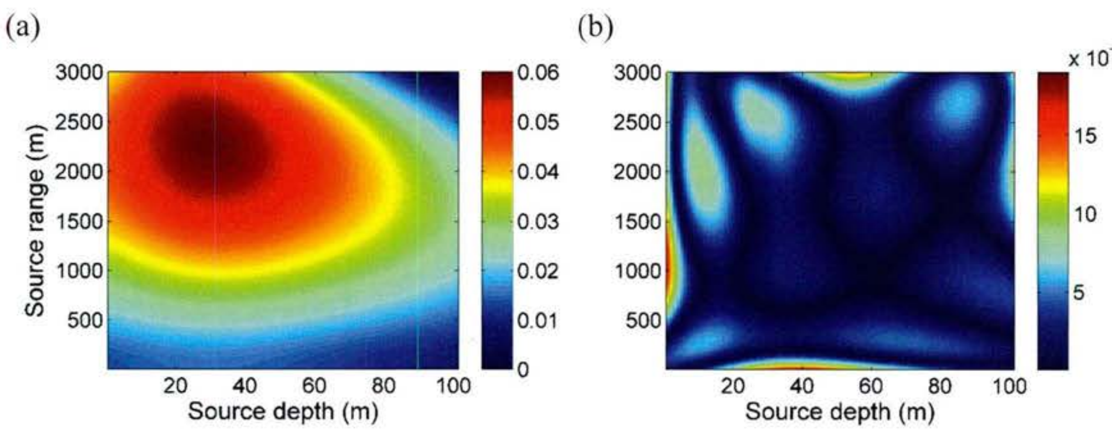

Figure 2. Difference in arrival times, t_{SSP}, obtained using a depth dependent sound speed profile and (a) arrival times, t_C, obtained using a constant sound speed profile (i.e. $t_{SSP} - t_C$); and (b) the constant sound speed model corrected with the best fit 2D polynomial, f, to (a) (i.e. $t_{SSP} - t_C - f$).

Parameterizing travel time surfaces significantly reduces run times required to maximize location ambiguity surfaces. Travel time offsets (errors) between the fitted travel-time surface and "true" SSP travel-time surface are fractions of milliseconds (Figure 2), which is adequate for model-based position estimates (i.e. increases in errors in resulting position estimates are minimal). This was an important step toward fully realizing the potential of multi-parameter inversions (Objective 1, which requires maximization in large parameter spaces) and multi-animal tracking (Objective 4, which requires maximization in multi-modal ambiguity surfaces).

Objective 3:

Using the RLD model-based localization method developed in this project, sound pressure levels can be used to roughly localize marine mammals with widely-spaced hydrophones (assuming source omni-directionalily and calibrated hydrophones). Comparison with localization results from model-based TDOA show that the RLD method is useful but that errors in position estimate are much larger than errors obtained using TDOA methods. One of the main reasons for large errors is violated assumptions of source omni-directionality and hydrophone calibration. Due to large errors, the RLD model-based localization method will be most useful in cases with non-synchronized hydrophones or when combined with timing-based localization methods.

Using both travel times and received levels for localization results in improved position estimates. Since positions estimates from the RLD method are generally less reliable than those from TOA methods, more weight is usually applied to the travel time contribution. In the case of non-synchronized hydrophone clocks, including RLD helps when inverting for clock offsets by contributing additional information.

The most impactful advantage of using RL instead of RLD is that source level is treated as an unknown parameter, which allows error in source level to be absorbed in the resulting source level estimate. Also, in the RLD method, estimated source position must account for the error associated with omni-directional source assumptions in the (ubiquitous) reality of directional sources. This produces unnecessarily large source position uncertainties which are reduced via the RL method. The improvement is especially important for localization of moderately directional sources (neither of the methods are applicable for highly directional sources).

Objective 4:

The MTDOA/MTOA methods account for multiple-animals by separating animals based on position. The methods do not require a TDOA/TOA association step, and false TDOAs/TOAs (e.g. a direct path associated with a multipath arrival) do not need to be removed. Figure 3 illustrates the approach for a case with 2 animals. The methods were thoroughly tested on simulated data and applied to the AUTEC multiple sperm whale dataset (4 simultaneously tracked animals on 5 hydrophones).

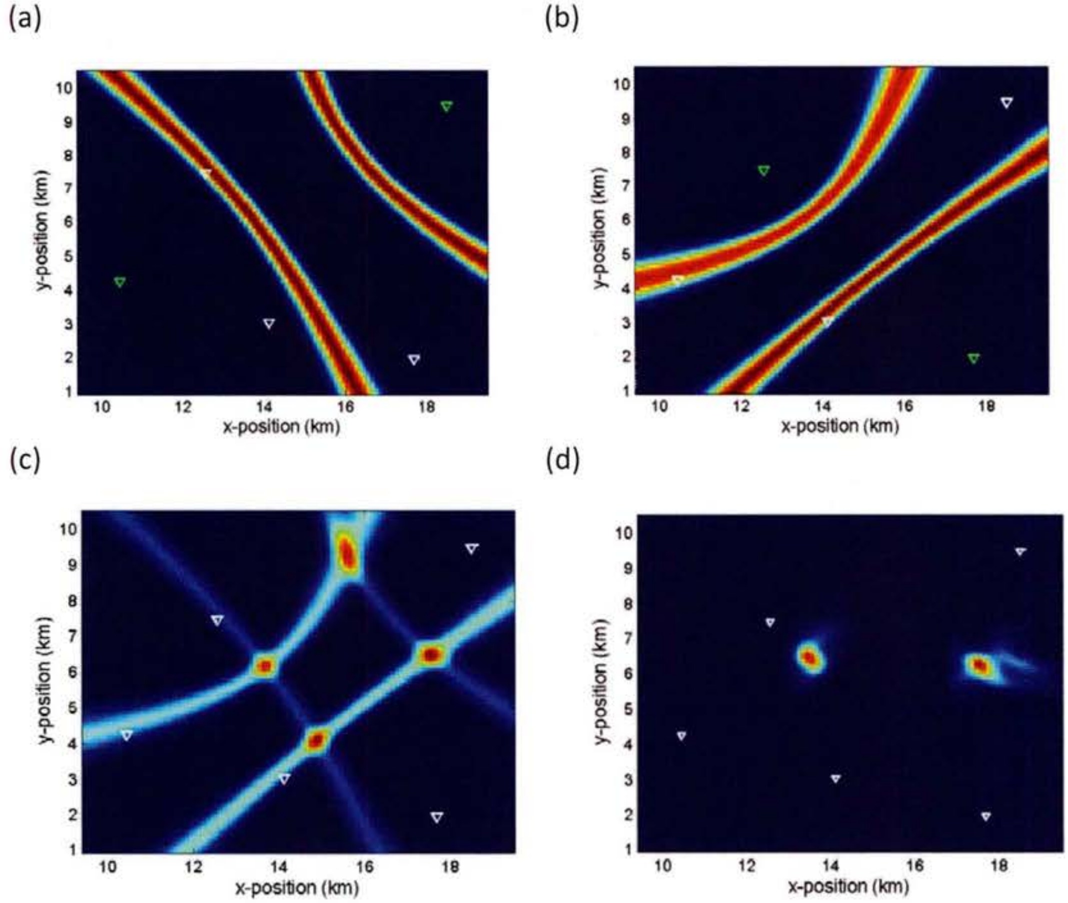

Figure 3 (a) For the hydrophones (triangles) shown in green, an ambiguity surface (red/blue indicate high/low probability of source presence) is created that incorporates all possible TDOAs (in this case 2). (b) A different pair hydrophones results in a second ambiguity surface. (c) Surfaces from (a) and (b) are multiplied to give 4 possible source locations. (d) Combining ambiguity surfaces from all receiver pairs reveals the 2 correct source positions. No source separation or association was required.

The advantages of including higher order arrivals when estimating animal location are well known. Most importantly, position estimates are improved and fewer hydrophones are required to localize. The MTDOA/MTOA methods using higher-order arrivals capitalize on these advantages without requiring arrivals to be classified (as direct, surface-reflected, etc) or associated between hydrophones. This has potential to help realize the goal of fully-automated localization in unfamiliar datasets. To validate the higher-order MTDOA/MTOA methods, they were applied to several datasets that have been well explored by the PI. Application to the case of a single sperm whale on 5 AUTEC hydrophones with well-defined surface reflections was straightforward and gave position estimates that were nearly as good as a method [from Nosal and Frazer 2007] that carefully classified and associated each click arrival [Figure 4]. A second application to a case with multiple animals gave position estimates that had smaller errors and smoother paths than using direct arrivals only.

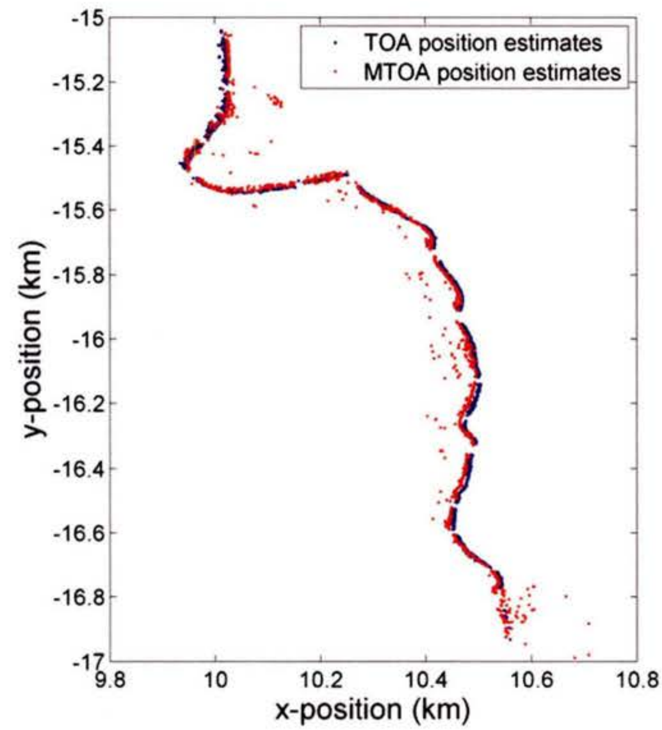

Figure 4. Comparison of position estimates from a TOA method that classifies and associates clicks and surface reflections prior to localization [from Nosal and Frazer 2007] and the MTOA method with higher-order arrivals developed here. The MTOA method assumed two arrivals: direct and surface-reflected. Position estimates from the MTOA method are similar to those from the TOA method but didn't require an association and classification step. Data are from the well-known DCLDE 2015 localization dataset: a sperm whale recorded on 5 bottom-mounted hydrophone at AUTEC.

Finally, the combined MTOA+RL method was applied to a dolphin click sequence from a single hydrophone dataset. Using arrival times only gave unreliable position estimates, primarily because there wasn't enough information in arrival alone and because arrival times had too much uncertainty to clearly resolve source positions. Including received levels was needed to produce reasonable location (range and depth) estimates [Figure 5].

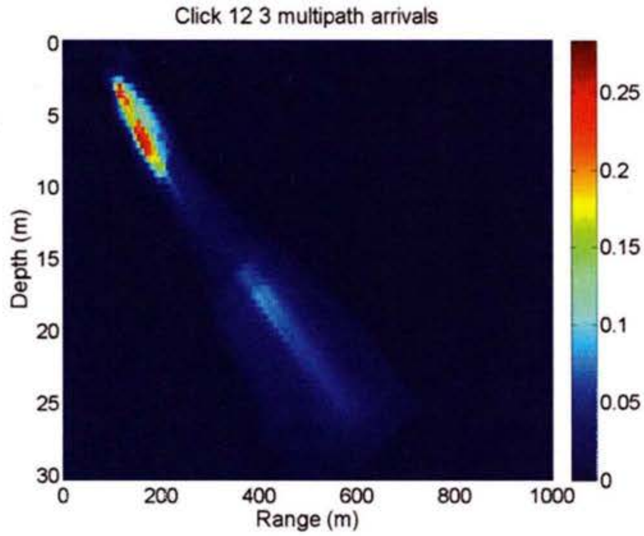

Figure 5. MTOA+RL ambiguity surface (red represents higher probability of source location) using the direct arrival and 3 multipath arrivals for a dolphin click recorded on a single seafloor-mounted hydrophone. The hydrophone [described in Fedenczuk et al. 2015] was tethered 5 meters off the seafloor in 30 m water depth.

IMPACT/APPLICATIONS

The localization and tracking methods developed in this project are useful for monitoring and studying marine mammal bioacoustics and behavior in the wild. Tracking results can be used to establish detection ranges and calling rates that are critical in density estimation applications. Methods developed to track marine mammals are useful for sources other than marine mammals (e.g. tracking of surface vessels can help to monitor fishing efforts in marine protected areas). Inverting marine mammal call recordings for environmental parameters in addition to source position has potential benefit in other acoustic and oceanographic applications.

RELATED PROJECTS

NSF award 1017775. Signal Processing Methods for Passive Acoustic Monitoring of Marine Mammals. (PI: E-M Nosal, Co PI: A Host-Madsen). Application of signal processing methods from speech and communications to passive acoustic monitoring of marine mammals. Focuses on detection and classification instead of on localization (this project). Progress made in this project directly benefits the proposed project (and vice versa).

ONR (Ocean Acoustics) N000141010334. Acoustic Seaglider: Philippine Sea Experiment (PI: B Howe, CoPI: E-M Nosal, G Carter, L VanUffelen). Use of gliders to record transmissions in the PhilSea10 tomography experiment. Some of the inverse methods used share similar theory and implementation. In the PhilSea project, the "unknown" of interest is sound speed (hence temperature and salinity) while in this project it is source location.

REFERENCES

Cato, DH (1998). Simple methods of estimating source levels and locations of marine animal sounds. *J. Acoust. Soc. Am.* 104: 1667 - 1678.

Collins MD, WA Kuperman (1991). Focalization: Environmental focusing and source localization. *J. Acoust. Soc. Am.* 90, 1410–1422.

Fialkowski LT, MD Collins, J Perkins, WA Kuperman (1997). Source localization in noisy and uncertain ocean environments. *J. Acoust. Soc. Am.* 101, 3539–3545.

Nosal E - M, LN Frazer (2007). Sperm whale three - dimensional track, swim orientation, beam patter, and click levels observed on bottom - mounted hydrophones. *J. Acoust. Soc. Am.* 122(4), 1969 - 1978.

McDonald MA, CG Fox (1999). Passive acoustic methods applied to fin whale population density estimation. J. Acoust. Soc. Am. 105(5), 2643 - 2651.

McDonald, MA, SE Moore (2002). Calls recorded from North Pacific right whales (Eubalaena japonica) in the eastern Bering Sea. *J. Cetacean Res. Manage.* 4:261 - 266.

Thode A (2000). Matched-field processing, geoacoustic inversion, and source signature recovery of blue whale vocalizations. *J. Acoust. Soc. Am.* 107(3), 1286-1300.

Thode A (2005). Three-dimensional passive acoustic tracking of sperm whales (Physeter macrocephalus) in ray-refracting environments. *J. Acoust. Soc. Am.* 18(6), 3575 - 3584.

Tiemann CO, MB Porter, LN Frazer (2004). Localization of marine mammals near Hawaii using an acoustic propagation model. *J. Acoust. Soc. Am.* 115(6), 2834 - 2843.

Tollefsen D, S Dosso (2009). Three - dimensional source tracking in an uncertain environment. *J. Acoust. Soc. Am.* 125(5), 2909 - 2917.

Wiggins S, M McDonald, LM Munger, S Moore, JA Hildebrand (2004). Waveguide propagation allows range estimates for North Pacific right whales in the Bering Sea. *Can. Acoust.* 32:146 - 154.

Zimmer W., Passive Acoustic Monitoring of Cetaceans. Cambridge University Press, Cambridge, 2011.

PUBLICATIONS

<u>Papers</u>

Nosal, E-M (2013). Methods for tracking multiple marine mammals with wide-baseline passive acoustic arrays. *J. Acoust. Soc. Am.* 134(3), 2383-2392 [refereed].

Book chapters

Mellinger DK, MA Roch, Nosal E-M, H Klink (2016). Signal Processing. In: Eds. WWL Au and MO Lammers, Listening in the Ocean – New Discoveries and Insights on Marine Life from Autonomous Passive Acoustic Recorders. Springer-Verlag New York

Nosal E-M (2013). Chapter 8: Model-based marine mammal localization methods. In: Eds. O Adam and F Samaran, Detection Classification and Localization of Marine Mammal using Passive Acoustics – 10 years of progress. Dirac NGO, Paris (Invited chapter)

Conference abstracts

Nosal E-M, Fedenczuk T (2015). Single hydrophone multipath ranging: Dealing with missing and spurious arrivals. San Diego, July 2015.

Rideout B, Nosal E-M, Host-Madsen A (2015). Acoustic multipath arrival time estimation via blind channel estimation. San Diego, July 2015.

Fedenczuk T, Smith B, Nosal E-M (2015). Single and four channel Acoustic Monitoring Packages (AMP-1 and AMP-4) for passive acoustic monitoring. San Diego, July 2015.

Rideout B, Nosal E-M, Host-Madsen A (2014). Obtaining underwater acoustic impulse responses via blind channel estimation. Meeting of the Acoustical Society of America, Oct 2014.

Nosal E-M (2013). Passive acoustic localization using received sound pressure levels. 6th International workshop on detection classification, localization and density estimation of marine mammals using passive acoustics. St. Andrews Scotland, June 2013.

Nosal, E-M (2012). Tracking multiple marine mammals using widely-spaced hydrophones. Acoustics Week in Canada, Banff, AB. 10-12 Oct, 2012.